

Using strong intense lasers to probe sterile neutrinos

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A linearly polarized laser beam acquires its circular polarization by interacting with a neutrino beam for the reason that the gauge-couplings of left-handed neutrinos are parity-violated. Based on this phenomena, we study the oscillations of active and sterile neutrinos in short baseline neutrino experiments. Using the total fluxes of active and sterile neutrinos in the $3 + 1$ framework, we show that the rate of generating circular polarization oscillates as a function of the distance L neutrinos propagating from the source to the detector. By measuring such oscillation, one can possibly determine the mixing amplitudes of active and sterile neutrinos and their squared-mass difference.

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I. INTRODUCTION

In the standard model (SM) of particle physics, three flavor eigenstates ν_α (ν_e, ν_μ, ν_τ) of active neutrinos participate in weak interactions. The flavor eigenstates ν_α (ν_e, ν_μ, ν_τ) mix with the mass eigenstates ν_i (ν_1, ν_2, ν_3) by a unitary matrix parametrized by three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and one CP-violating phase δ . Several experiments studying solar, atmospheric and reactor active neutrinos in past years provide strong evidences supporting the existence of active neutrino oscillations [1], implying that active neutrinos are not exactly massless although they chirally couple to gauge bosons. (long- baseline neutrino oscillations). The values of $\theta_{12}, \theta_{13}, \theta_{23}$ and Δm_{ij}^2 are obtained from an up-to-date global analysis [2] of solar, atmospheric, reactor and accelerator neutrino data, as well as the long-baseline experiments with $E_\nu/L \sim \Delta m_{12}^2 \simeq 5 \times 10^{-3} \text{eV}^2$, where E_ν and L respectively are the neutrino energy and the travel distance from source to detector.

However, a few anomalous results have emerged in short-baseline neutrino oscillation measurements and in cosmological data analysis, which cannot be accommodated in the scheme of active neutrino oscillations (see for review [3]). The most popular interpretation of such anomalies is based on a simple extension of the scheme of active neutrino oscillations, involving new additional light sterile neutrinos with mass in the eV range [4].

The right-handed neutrino fields are fundamentally different from the other elementary fermion fields because they are invariant under the symmetries of the SM: they are singlets of $SU_c(3) \times SU_L(2) \times U_Y(1)$ gauge symmetries. These right-handed neutrino fields are called sterile [5] because they do not participate in weak, strong and electromagnetic interactions, and associate only with gravitational interaction. By the theory, the number and mass of right-handed neutrino fields are not constrained. The essential characteristic of these fields is that they are singlets under the SM symmetries, and hence sterile. Therefore, the short-baseline experiments (see for example [6–9]) are important for observing neutrino oscillations with $E_\nu/L \sim \Delta m^2 \sim \text{eV}^2$. This is crucial in the neutrino physics [4] to check the existence of sterile neutrinos, their mass scale and mixing with normal active neutrinos.

Recently it is shown that for the reason of active neutrinos being left-handed and their gauge-couplings being parity-violated, linearly polarized laser photons acquire their circular polarizations by interacting with neutrino beams [10]. This phenomenon can possibly be used to detect the fluxes of active neutrinos, so as to gain some insight into the physics of active and sterile neutrino oscillations. In this Letter, we calculate the total flux of active and sterile neutrinos at a fixed distance L from the source to the detector of active neutrinos (the source-detector distance in

short), so as to determine the amplitude $[\sin^2(2\theta_{\alpha s})]$ of the active neutrino ν_α and the sterile neutrino ν_s oscillations, as well as the mass-squared difference

$$\Delta m^2 = m_s^2 - m_i^2 \quad (1)$$

where m_s and m_i indicate the masses of sterile and active neutrinos.

First we shortly recall the some theoretical and experimental results on the short-baseline neutrino oscillations. After discussing the time evaluation of the total fluxes of neutrino beams as a function of the source-detector distance L , we calculate the generation of circularly polarized laser beam due to the interaction of a linear polarized laser beam with an active neutrino beam. We show how the mass- squared difference Δm^2 of Eq. (1) and the total fluxes of active and sterile neutrinos can be possibly determined by measuring the circular polarization of the laser beam interacting with active neutrino beam at the different source-detector distance L .

II. STERILE NEUTRINO IN 3 + 1 MODEL

According to the neutrino mixing hypotheses, flavor neutrinos ν_l are superpositions of the mass eigenstates labeled with ν_i as follows [for example see [11]]

$$\nu_l = \sum_{i=1}^{3+n_s} U_{li} \nu_i \quad (2)$$

where $l = e, \mu, \tau$ and $i = 1, 2, 3, \dots, n_s$. Here n_s indicates the number of possible sterile neutrino species. The active flavor neutrinos ν_l are identified by their charged current interactions with gauge bosons W_μ^\pm .

$$\mathcal{L}_{\text{int}} = \frac{g_w}{2\sqrt{2}} \sum_{l,i} \left[\bar{\psi}_{\nu_i} \gamma^\mu (1 - \gamma^5) U_{li} \psi_l W_\mu^+ + \bar{\psi}_l \gamma^\mu (1 - \gamma^5) U_{li}^\dagger \psi_{\nu_i} W_\mu^- \right], \quad (3)$$

where the summations are over $l = e, \mu, \tau$; $i = 1, 2, 3, \dots, n_s$. In the case $n_s = 1$, i.e., the 3 + 1 model, the mixing matrix U is represented as a 4×4 unitary matrix. In the following, we adopt the parametrization used in Ref. [12],

$$U \equiv \begin{pmatrix} 1 & 0 \\ 0 & U_{\text{PMNS}} \end{pmatrix} \cdot U_s \quad (4)$$

where U_{PMNS} is the standard 3×3 PMNS matrix containing mixing elements between different flavors of active neutrinos, and U_s represents a 4×4 mixing matrix between the sterile neutrino and active neutrinos. The mixing matrix U_s is parameterized with rotation angles (γ, α, β) and phase factors (δ_1, δ_2) [12].

Assuming that all CP-phases (δ_1, δ_2) are zero and $m_s \gg m_1, m_2, m_3$, therefore one has $\Delta m^2 \equiv \Delta m_{si}^2 \gg \Delta m_{12}^2, \Delta m_{13}^2, \Delta m_{23}^2$ [9]. Since the effects of oscillations depends on the sum of the mass-squared differences of two neutrino species, one keeps the leading term Δm^2 by neglecting the small mass-squared differences $\Delta m_{12}^2, \Delta m_{23}^2$ and Δm_{13}^2 for short baseline experiments [11]. As a result, the probabilities of an active α -neutrino oscillating to another active β -neutrino, and to the sterile neutrino ν_s can be written as follows (see for example Ref. [11])

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)(U_{\alpha 0}U_{\beta 0} \sum_{i=1}^3 U_{\alpha i}U_{\beta i}), \quad (5)$$

and

$$P(\nu_\alpha \rightarrow \nu_s) = \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)(U_{\alpha 0}U_{00} \sum_{i=1}^3 U_{\alpha i}U_{0i}). \quad (6)$$

On the other hand, the oscillation probability of the two-flavor $\nu_\mu \leftrightarrow \nu_e$ oscillation is given by, (see for example Ref. [11])

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{\mu e}) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right). \quad (7)$$

Comparing Eq. (5) with Eq. (7), one has

$$\sin^2(2\theta_{\mu e}) = U_{\mu 0}U_{e0} \sum_{i=1}^3 U_{\mu i}U_{ei}, \quad (8)$$

where $[\sin^2(2\theta_{\mu e})]$ is the amplitude of neutrino oscillation $[\nu_\mu \rightarrow \nu_e]$. Analogously, one can obtain the amplitude of electron disappearance $[\sin^2(2\theta_{ee})]$ and the amplitude of muon disappearance $[\sin^2(2\theta_{\mu\mu})]$ in terms of the unitary U matrix elements (4). In addition, we can rewrite Eq. (6) as

$$P(\nu_\alpha \rightarrow \nu_s) \approx \sin^2(2\theta_{\alpha s}) \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right), \quad (9)$$

by defining the amplitude of neutrino oscillation $\nu_\alpha \leftrightarrow \nu_s$

$$\sin^2(2\theta_{\alpha s}) = (U_{\alpha 0}U_{00} \sum_{i=1}^3 U_{\alpha i}U_{0i}). \quad (10)$$

In the short baseline experiments for the two-flavor $\nu_\mu \leftrightarrow \nu_e$ oscillation, the ranges of $0.2 \text{ eV}^2 < \Delta m^2 < 10 \text{ eV}^2$ and $0.01 \text{ eV}^2 < \Delta m^2 < 1 \text{ eV}^2$ are respectively discussed by the LSND [6] and MiniBooNE [7] experiments. Combining the results of the experiments KARMEN [8], ICARUS [13], LSND and MiniBooNe [7] all together, one obtains [14, 15] $\Delta m^2 \sim 0.5 \text{ eV}^2$ and

$$\sin^2 2\theta_{\mu e} \sim 0.0015, \quad \sin^2 2\theta_{\mu\mu} \sim 0.03 - 0.05, \quad \sin^2 2\theta_{ee} \sim 0.093 - 0.13. \quad (11)$$

Reactor experiments have played an important role in the establishment of the short baseline oscillation. In short baseline experiments at distances $L < 100$ m from the reactor core, at ILL-Grenoble, Goesgen, Rovno, Krasnoyarsk, Savannah River and Bugey [16], the measured rate of $\bar{\nu}_e$ was found to be in a reasonable agreement with that predicted from the reactor antineutrino spectra, though slightly lower than theoretically expected, with the measured/ expected ratio at 0.976 ± 0.024 . Neutrino oscillations in distances $L < 100$ m from the reactor core are not expected in the theoretical scenario of flavor mixing of three active neutrinos without sterile neutrinos. In the short baseline experiments based on these reactors, the deviation of experimental data from theoretical expectations is called the reactor anomaly [17]. Another deviation of experimental data of neutrino fluxes from theoretical estimations based on the flavor mixing of three active neutrinos is related to the GALLEX and SAGE experiments. This deviation is called the gallium anomaly [9, 18]. Both the reactor and gallium anomalies can possibly be interpreted in the 3+1 framework with $\Delta m^2 \gtrsim 1 \text{ eV}^2$ and $\sin^2 2\theta_{ee} \sim 0.17$ [14, 19]. In Ref. [15], the global analysis of the short baseline neutrino oscillation in the scheme of the 3+1 neutrino mixing determines $0.82 \text{ eV}^2 < \Delta m^2 < 2.19 \text{ eV}^2$ at the 3σ -level, and the assumption of no oscillation between flavor and sterile neutrinos is excluded at 6σ -level.

III. THE TIME EVALUATION OF ACTIVE NEUTRINO FLUX

Suppose that (i) the initial total energy flux $F_\nu(0)$ of active neutrinos produced from the source consists of the electron neutrino flux $F_{\nu_e} = \mathcal{C}F_\nu(0)$ and muon neutrino flux $F_{\nu_\mu} = (1 - \mathcal{C})F_\nu(0)$, where $\mathcal{C} < 1$; (ii) there is the oscillation between the active neutrinos and light sterile neutrinos, this means that total flux of active neutrinos is a function of the source-detector distance L in the short baseline experiments. Thus we can write the total flux of active neutrinos as

$$\begin{aligned} F_\nu(L) &= F_\nu(0) - c \int \frac{d^3q}{(2\pi)^3} [q f_{\nu_e} P_{\nu_e \rightarrow \nu_s} + q f_{\nu_\mu} P_{\nu_\mu \rightarrow \nu_s}] \\ &= F_\nu(0) - F_{\nu_s}(L), \end{aligned} \tag{12}$$

where $E_\nu \simeq q_\nu$, f_{ν_e, ν_μ} are the energy-distribution functions of neutrino beams, and the second term on the right-handed side indicates the total flux F_{ν_s} of sterile neutrinos, which propagates approximately in the speed of light c for $E_{\nu_s} \simeq q_{\nu_s} \gg m_{\nu_s}$.

On the other hand, because electron and muon neutrinos are oscillating each other while they are propagating, the fluxes $F_{\nu_e}(L)$ and $F_{\nu_\mu}(L)$ of electron and muon neutrinos are related each other as a function of the source-detector distance L . Using Eq. (5), we write the total energy flux

of the active flavor neutrinos as

$$\begin{aligned}
F_\nu(L) &= F_{\nu_e}(L) + F_{\nu_\mu}(L) \\
&= c \int \frac{d^3q}{(2\pi)^3} \left[(P_{\nu_e \rightarrow \nu_e} + P_{\nu_e \rightarrow \nu_\mu} + P_{\nu_e \rightarrow \nu_\tau}) q f_{\nu_e} \right. \\
&\quad \left. + (P_{\nu_\mu \rightarrow \nu_\mu} + P_{\nu_\mu \rightarrow \nu_e} + P_{\nu_\mu \rightarrow \nu_\tau}) q f_{\nu_\mu} \right].
\end{aligned} \tag{13}$$

Suppose that the initial neutrino beam has a very narrow energy distribution around the average neutrino energy \bar{E}_ν , and a very small angular distribution (divergence angle) that can be negligible.

Using Eq. (6), we write the neutrino energy fluxes (13) as follows,

$$\begin{aligned}
F_\nu(L) &= F_{\nu_e}(0) \left(1 + [-\sin^2(2\theta_{ee}) + \sin^2(2\theta_{e\mu}) + \sin^2(2\theta_{e\tau})] \sin^2\left(\frac{\Delta m^2 L}{4\bar{E}_\nu}\right) \right) \\
&\quad + F_{\nu_\mu}(0) \left(1 + [-\sin^2(2\theta_{\mu\mu}) + \sin^2(2\theta_{\mu e}) + \sin^2(2\theta_{\mu\tau})] \sin^2\left(\frac{\Delta m^2 L}{4\bar{E}_\nu}\right) \right),
\end{aligned} \tag{14}$$

which are only functions of neutrino average energy \bar{E}_ν and the source-detector distance L .

Using Eqs. (12), (13) and (14), we approximately obtain the total sterile neutrino flux

$$\begin{aligned}
F_{\nu_s}(L) &\approx F_\nu(0) \left[\mathcal{C} (\sin^2(2\theta_{ee}) - \sin^2(2\theta_{e\mu}) - \sin^2(2\theta_{e\tau})) \right. \\
&\quad \left. + (1 - \mathcal{C}) (\sin^2(2\theta_{\mu\mu}) - \sin^2(2\theta_{\mu e}) - \sin^2(2\theta_{\mu\tau})) \right] \sin^2\left(\frac{\Delta m^2 L}{4\bar{E}_\nu}\right) \\
&= F_\nu(0) \left[\mathcal{C} \sin^2(2\theta_{es}) + (1 - \mathcal{C}) \sin^2(2\theta_{\mu s}) \right] \sin^2\left(\frac{\Delta m^2 L}{4\bar{E}_\nu}\right),
\end{aligned} \tag{15}$$

where we define

$$\begin{aligned}
\sin^2(2\theta_{\mu s}) &\equiv \sin^2(2\theta_{\mu\mu}) - \sin^2(2\theta_{\mu e}) - \sin^2(2\theta_{\mu\tau}), \\
\sin^2(2\theta_{es}) &\equiv \sin^2(2\theta_{ee}) - \sin^2(2\theta_{e\mu}) - \sin^2(2\theta_{e\tau}),
\end{aligned} \tag{16}$$

i.e., the mixing angles between active and sterile neutrinos are expressed in terms of the mixing angles between different active neutrinos. These results of Eqs. (12), (14) and (15) show that the total fluxes of active and sterile neutrinos oscillate each other while they are propagating from the active neutrino source to detector in the short-baseline experiments.

IV. OSCILLATION OF CIRCULAR POLARIZATION OF LASER BEAM

As discussed in Ref. [10], for the reason of active neutrinos being left-handed and their gauge-couplings being parity-violated, the circular polarization of laser photons is generated by interactions between a linearly polarized laser beam with an active neutrino beam. The intensity of circular polarization represented by the Stock V-parameter is expressed in terms of the intensity

Q of linearly polarized laser beam and the total flux $F_\nu(L, \bar{E}_\nu)$ of the active Dirac neutrino beam [10]

$$\frac{\Delta V}{Q} \approx 2.37 \cdot 10^{-36} (\text{cm}^2) \left(\frac{F_\nu(L, \bar{E}_\nu)}{k} \right) \Delta t, \quad (17)$$

where k is the mean energy of laser photons, Δt is the interacting time of laser beams with the active neutrino beam at the source-detector distance L . Note that we do not consider here the circular polarization produced due to the interaction of laser beam directly with sterile neutrinos, for the reason that laser photons coupling to sterile neutrinos is assumed to be very small, compared with their coupling to active neutrinos. The presence of active and sterile neutrinos mixing and the oscillation leads to the oscillating nature of the total flux $F_\nu(L, \bar{E}_\nu)$ of active neutrinos. As a result, Eq. (17) clearly shows that the circular polarization $\Delta V/Q$ oscillates as a function of the source-detector distance L .

Based on the oscillation from active neutrinos to sterile neutrinos (15) in the short baseline experiments, we estimate the rate of generating circular polarization of laser photons at the source-detector distance L

$$R_V(L) \approx \frac{1}{k} \sigma_{\text{laser}} f_{\text{pulse}} \tau_{\text{pulse}} \Delta V(L), \quad (18)$$

where τ_{pulse} is the time duration of a laser pulse, the effective area of photon-neutrino interaction is represented by the laser-beam size σ_{laser} being smaller than the neutrino-beam size Δd , and the laser repetition rate f_{pulse} is the number of laser pulses per second. To have more efficiency, we assume that laser and neutrino beams are synchronized and the f_{pulse} is equal to the repetition rate of neutrino beam f_{bunch} , which is the number of neutrino bunches per second. Using Eqs. (15-18), the rate of generating circular polarization of laser photons is given as a function of the source-detector distance L

$$R_V(L) = R_V(0) \left[1 - (\mathcal{C} \sin^2(2\theta_{es}) + (1 - \mathcal{C}) \sin^2(2\theta_{\mu s})) \sin^2\left(\frac{\pi L}{L_{\text{osc}}}\right) \right], \quad (19)$$

where

$$L_{\text{osc}} = \frac{4\pi \bar{E}_\nu}{\Delta m^2}; \quad R_V(0) = \frac{1}{k} \sigma_{\text{laser}} f_{\text{pulse}} \tau_{\text{pulse}} \Delta V(L=0). \quad (20)$$

If we consider the mean energy of neutrino beam $\sim 1 \text{ GeV}$ and $\Delta m^2 \sim 1 \text{ eV}^2$, the oscillation length $L_{\text{osc}} \simeq 2.5 \text{ Km}$. As shown in Fig.(1), the oscillation has its minimum at $L = nL_{\text{osc}}/2$ and maximum $L = (n+1)L_{\text{osc}}/2$, $n = 1, 2, 3, \dots$. Measuring the value $L = L_{\text{osc}}/2$, one can determine the value of Δm^2 the squared-mass difference of active and sterile neutrinos, thus approximately obtain the sterile neutrino mass m_{ν_s} for $m_{\nu_s} \gg m_{\nu_i}$.

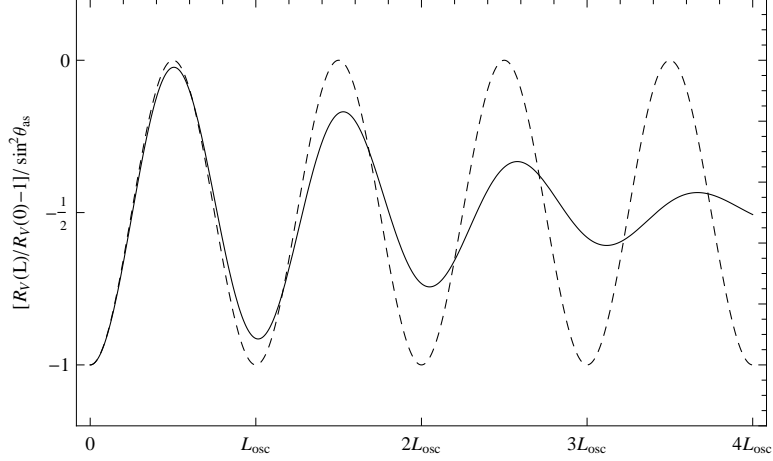


FIG. 1. This plot shows the oscillation of $(R_V(L) - R_V(0))/R_V(0) \sin^2 2\theta_{as}$ as a function of the source-detector distance L , where $\sin^2 2\theta_{as} \equiv \mathcal{C} \sin^2(2\theta_{es}) + (1 - \mathcal{C}) \sin^2(2\theta_{\mu s})$. The initial neutrino beam flux at $L = 0$ consists of electron and muon neutrinos. Here we assume the mean energy of neutrino beam $\bar{E}_\nu \sim 1 \text{ GeV}$. The dashed line represents the neutrino oscillations for the case that the neutrino beam has a very sharp energy distribution around \bar{E}_ν . The solid line represents the neutrino oscillations for the case that the neutrino beam has a Gaussian energy distribution with the mean energy \bar{E}_ν and spreading width $\sigma = 0.1 \bar{E}_\nu$.

As discussed in Refs. [10, 20], with a neutrino beam $\bar{F}_\nu \sim 10^4 \text{ GeV cm}^{-2} \text{ sec}^{-1}$ (see for example [21]) and a linearly polarized laser beam of energy $k \sim \text{eV}$ and power $\bar{P}_{\text{laser}} \simeq 10 \text{ MW}$, the rate of generating circularly polarized photons $R_V(L=0) \sim 1/\text{sec}$ ($\sim 9 \times 10^4/\text{day}$). This value $R_V(L)$ depends on the compositions (\mathcal{C}) of the initial neutrino beam. For a pure muon (electron) neutrino beam at $L = 0$, we have $R_V(L)/R_V(0) - 1 < 0.05$ (0.13) (see Eq. (11)). For the case of mixing muon-electron neutrino beam $R_V(L)/R_V(0) - 1 < 0.13\mathcal{C} + 0.13(1 - \mathcal{C}) < 0.13$. If we use an electron neutrino beam with the mean energy $\sim \text{GeV}$ ($\Delta m^2 \sim 1 \text{ eV}^2$), the rate of generating circularly polarized photons decreases about 13% at $L = L_{\text{osc}}/2$, i.e., $R_V(L_{\text{osc}}/2) \sim 0.87/\text{sec}$, in comparison with $R_V(L=0) \sim 1/\text{sec}$ at $L = 0$. This variation should be detectable so as to determine Δm^2 , $\sin^2(2\theta_{es})$ and $\sin^2(2\theta_{\mu s})$ by Eq. (19). Considering the damping of neutrino oscillations with the distance L (see Fig. 1), one should appropriately measure the locations of first three minimal (or maximal) values of $R_V(L)$ at $L = L_{\text{osc}}/2, 3L_{\text{osc}}/2$ and $5L_{\text{osc}}/2$ so that Δm^2 , $\sin^2(2\theta_{es})$ and $\sin^2(2\theta_{\mu s})$ can be determined.

V. CONCLUSION AND REMARKS

In this Letter, we give a brief discussion on the possible relation of the anomalies observed in short baseline experiments to the oscillation between active and sterile neutrinos. In order to measure the oscillation amplitudes and squared mass difference in short baseline experiments, we propose the interacting of laser beams with the neutrino beam and measuring the generated circular polarization of laser photons. This bases on the result [10] that the circular polarization of laser photons is generated by the collision of laser and neutrino beams. This phenomenon was also considered [20] for obtaining the power spectrum C_l^V of the circular polarization of CMB photons. As discussed in Ref. [10], the rate of generating the circular polarization of laser photons should be large enough for experimental measurements. In conclusion, this proposal should add a valuable information for understanding the physics of sterile neutrinos and their oscillations with active neutrinos.

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